

Risk-informed design of seismic isolation systems for nuclear facilities

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Outline

- Regulatory guidance for seismic isolation
 - Performance expectations
 - DOE and NRC commonalities
 - US seismic isolation hardware
- Risk calculations in DOE and NRC space
- On-going nuclear-related studies

Earthquake simulators

- Two high-performance simulators
- 7m by 7m platforms
- Located in a trench
- 50T payload/simulator
- 0 to 50 Hz at 50T
- Equipment qualification
 - 6 components of input
 - Substation equipment; A/E/M/P systems; NPP; tanks
 - IEEE 693, AC 156, GR 63 Core, NQA-1



Geo laminar box

- 1D input
- 6m tall; 5m by 2.7m in plan; 80m³ of soil
- Instrumentation
 - Shape arrays
 - Acceleration, displacement
- Soil-foundation interaction
- Soil-structure interaction
- Validation of numerical codes
 - Site response
 - SSI



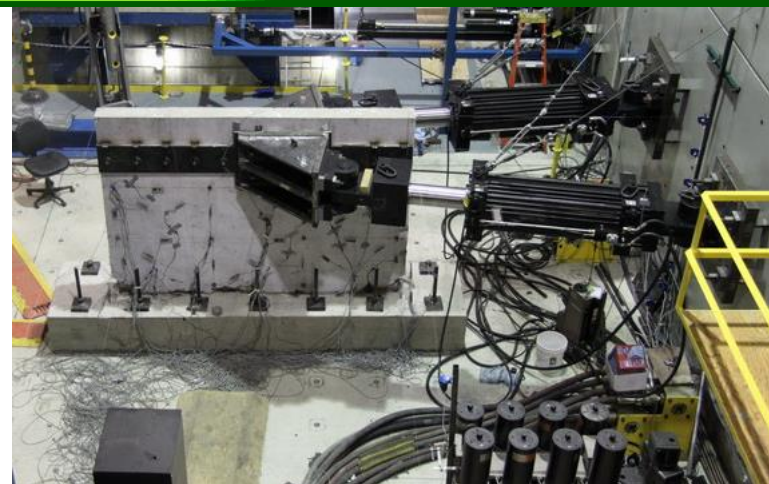
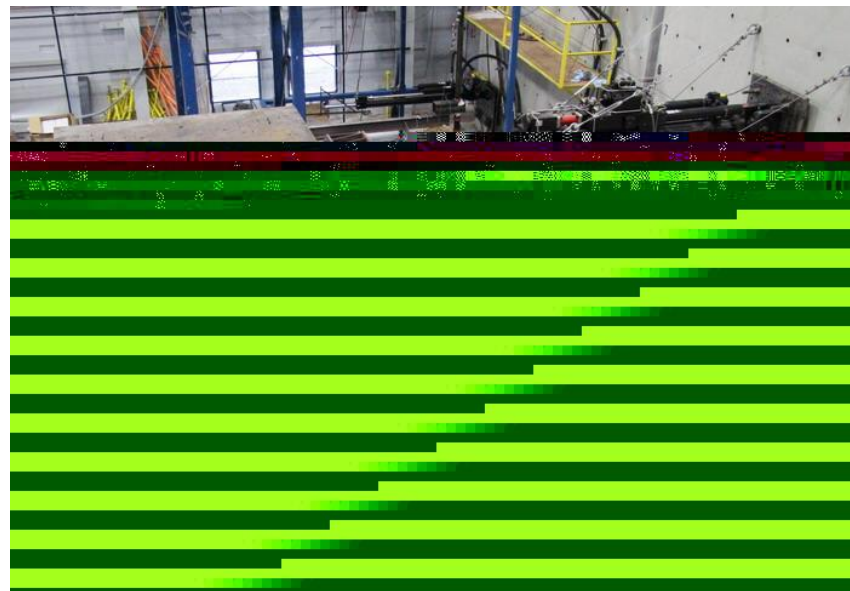
Nonstructural simulator

- Two-level systems
- Large displacement ($\pm 1\text{m}$), high velocity (2.5m/s), frequency (5 Hz)
- Impose acceleration and drift histories simultaneously
- Systems of acceleration and displacement-sensitive components
- Derive fragility functions
- Tested to date
 - Non-load bearing walls
 - Piping systems
 - Hybrid nonstructural systems

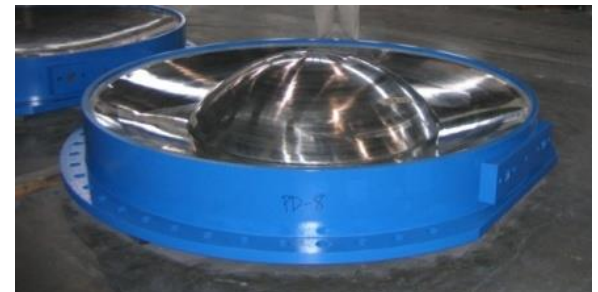
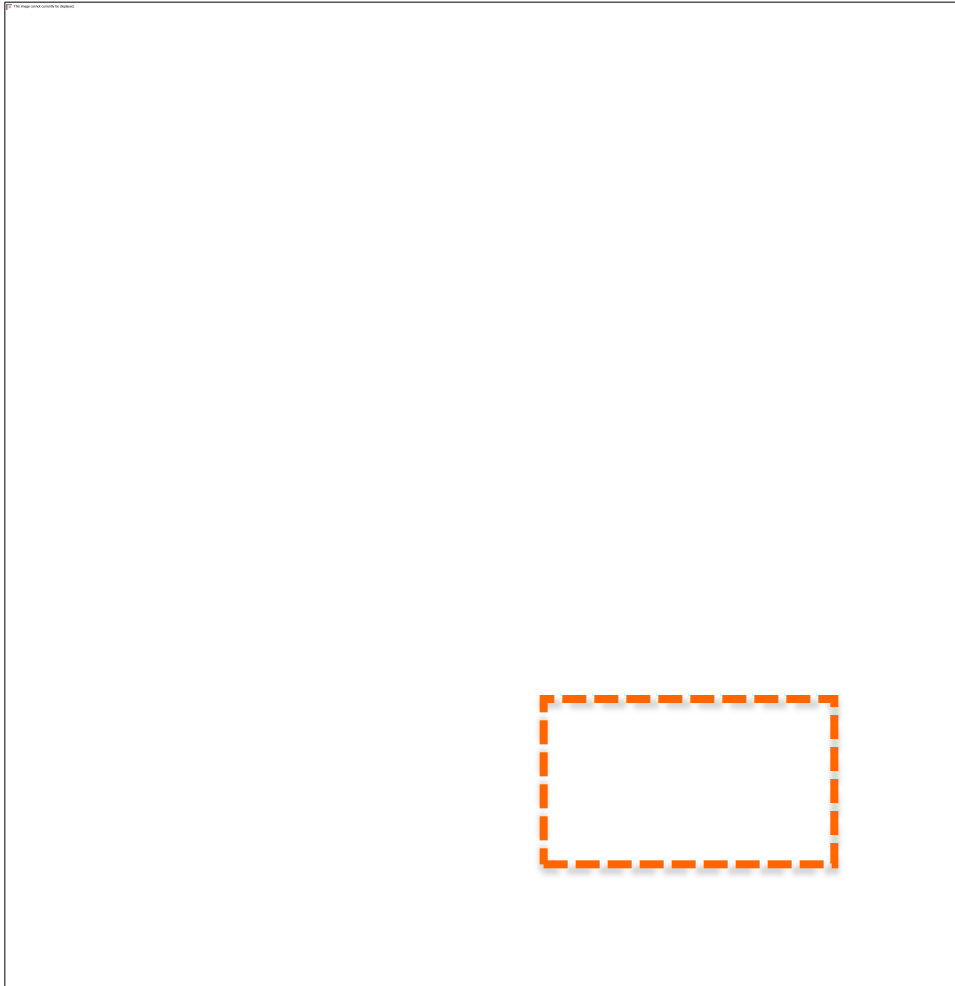


Actuators

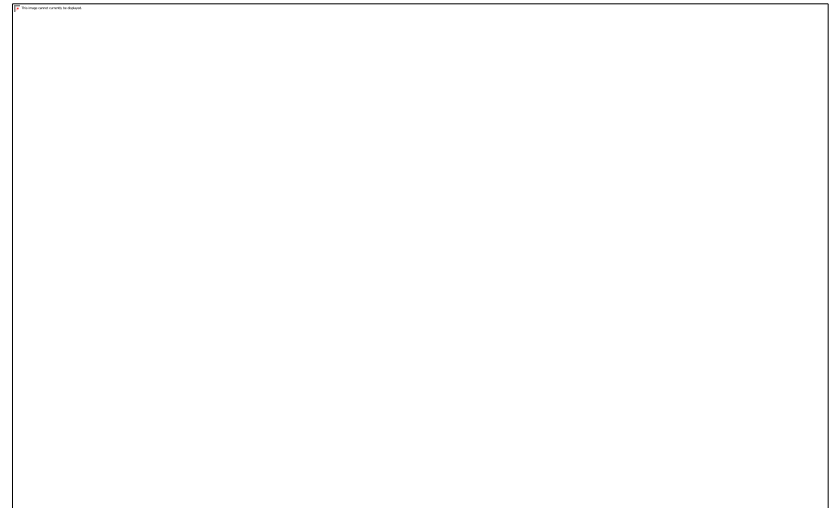
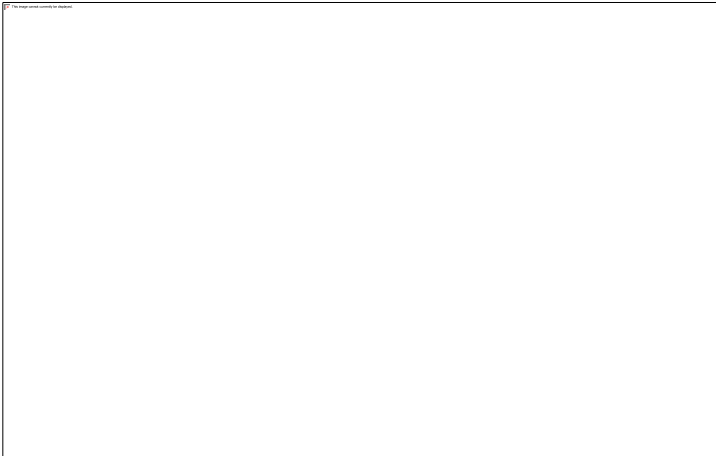
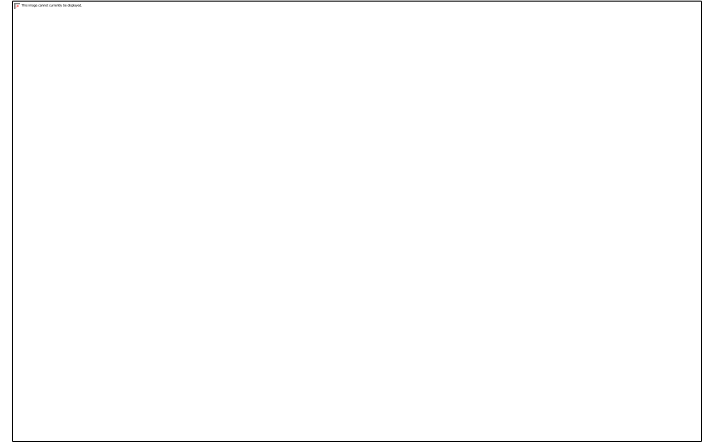
- Three dynamic
 - 100T, 1.5m/sec, ± 0.5 m
- Two static
 - 200T, ± 0.5 m
- Strong wall, floor
- Tests to date
 - Steel, SC and concrete walls
 - Steel braced frames
 - Hybrid simulations

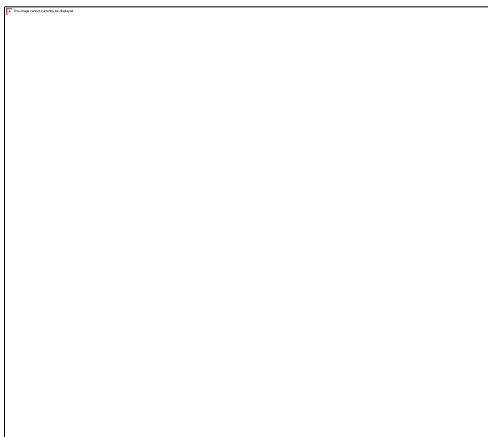
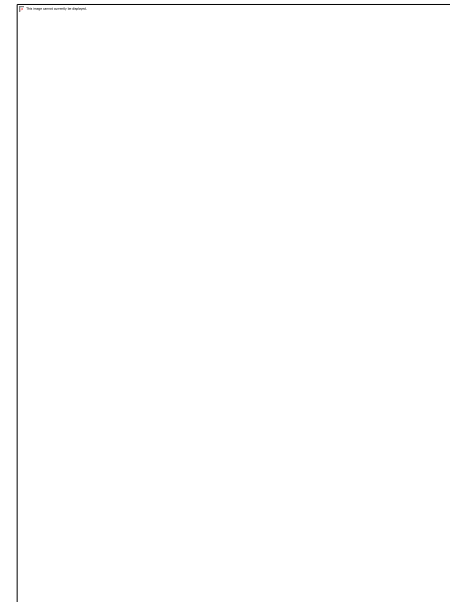
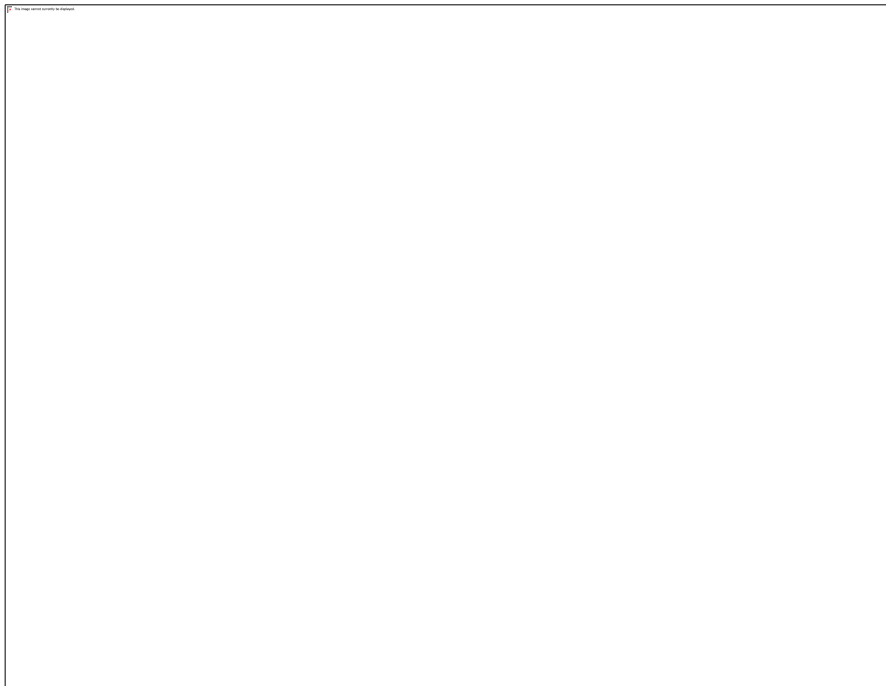


Regulatory guidance for isolation

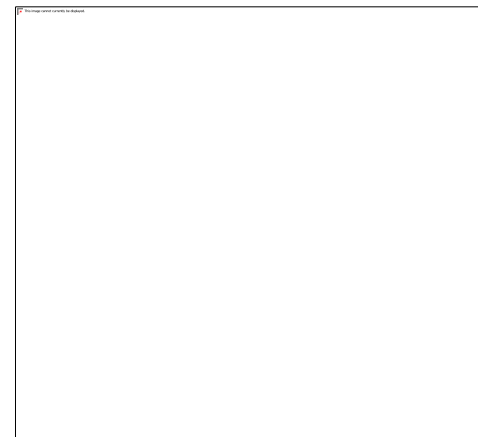


Seismic isolation





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Regulatory guidance for isolation

- ASCE 4-14, Chapter 12: analysis, design, testing
- ASCE 43-**, Chapter 10: design, testing
- Seismic isolation NUREG
- Horizontal isolation only
- *Surface*-mounted nuclear facilities
- Prequalified seismic isolators: LRB, LDRB, FPB
- DOE and NRC provisions applicable in principle to
 - Components and systems
 - Deeply embedded facilities
 - Small modular reactors
 - Three-dimensional isolation systems
- Prequalification of alternate systems

Regulatory guidance for isolation

- Performance expectations of ASCE 43, SDC 5
 - FOSID at MAFE = E-5
 - DBE = DF * UHS at E-4 = GMRS
 - 1% NEP for 100% DBE shaking
 - 10% NEP for 150% DBE shaking
- Analyzable for beyond design basis loadings
 - Definitions differ for DOE and NRC applications
- Reliable numerical models of isolators
 - Validated by full-scale dynamic testing
- Modeling and analysis of isolated structures
- Prototype and production testing

Regulatory guidance for isolation

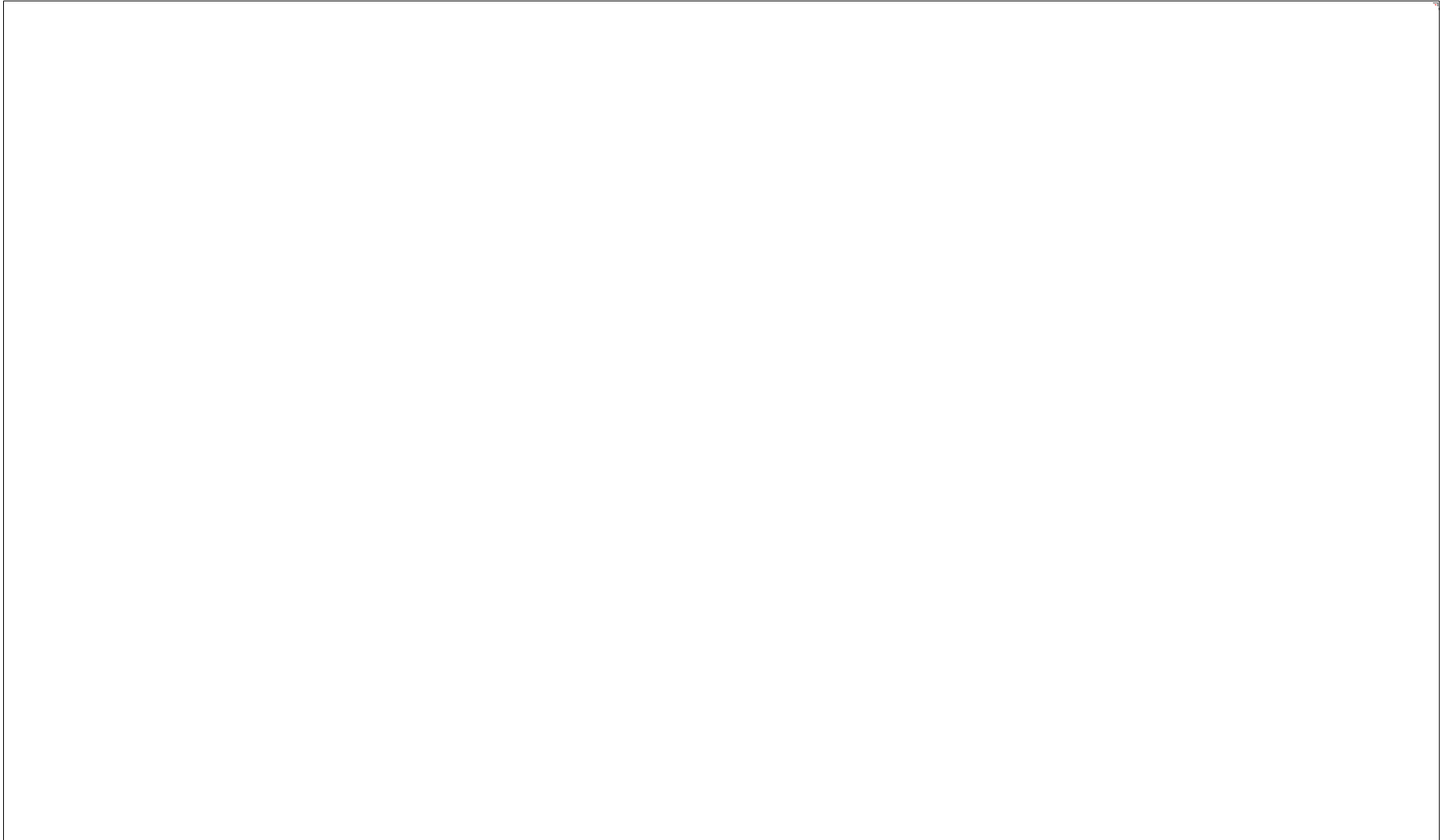
- Fully coupled, nonlinear time-domain
 - Soil (LB, BE, UB), isolators, SSCs
 - ABAQUS, LS-DYNA, NRC ESSI
 - Used for all types of isolators
 - 3D soil domain, domain reduction method
 - Apply ground motions at boundary of model
- Full coupled, frequency domain
 - LDR bearings
- Multi-step
 - Frequency domain analysis to compute SIDRS; equivalent linear models of isolators
 - Ground motions matched to SIDRS
 - Nonlinear analysis of isolated superstructure

Regulatory guidance for isolation

- Performance statements
 - Isolators suffer no damage in the DBE
 - Confirm by testing all isolators
 - Isolated facility impacts surrounding structure
 - 1% NEP for DBE shaking; 10% NEP for BDBE shaking
 - Isolators sustain gravity and earthquake induced axial loads at 90%-ile BDBE displacement
 - Confirm by prototype testing
 - Safety-critical umbilical lines sustain 90%-ile BDBE displacement with 90% confidence
 - Confirm by testing and/or analysis

Regulatory guidance for isolation

- Prototype tests
 - 3 minimum of every type and size
 - Dynamic tests to interrogate isolator behavior
 - Design basis and beyond design basis
 - Clearance to the stop (CS)
 - Cycles consistent with EDB shaking demands
 - Damage acceptable for CS tests
- Production tests
 - Isolators identical to prototype isolators
 - QA/QC testing of all isolators
 - Static or dynamic tests
 - Design basis loadings
 - No damage acceptable for design basis tests
- ASME-NQA-1 quality program, or equivalent

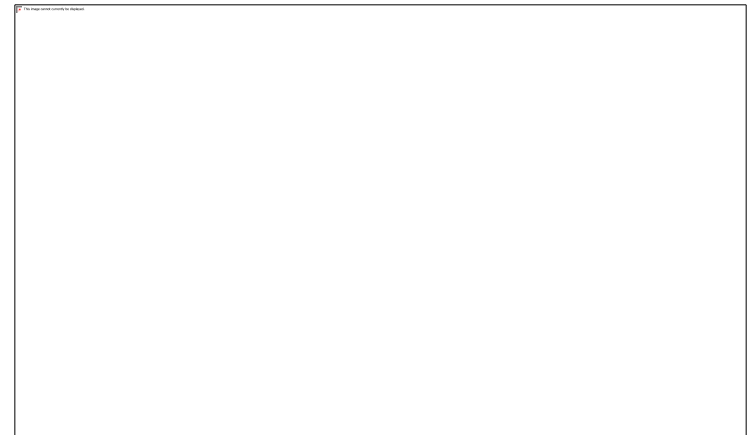
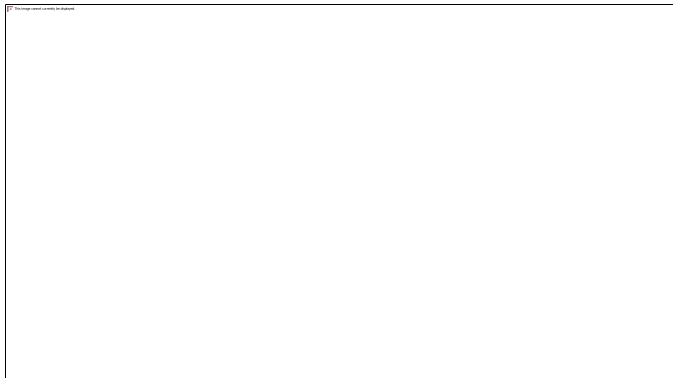


Isolators and isolation systems

- Addressed for US practice
 - Low damping natural rubber
 - Lead-rubber
 - Spherical sliding (FP) bearing
- Acknowledged in the NUREG/ASCE 4/ASCE 43
 - High-damping rubber
 - Synthetic rubber (neoprene)
 - EradiQuake
 - 3D isolation systems

Isolators and isolation systems

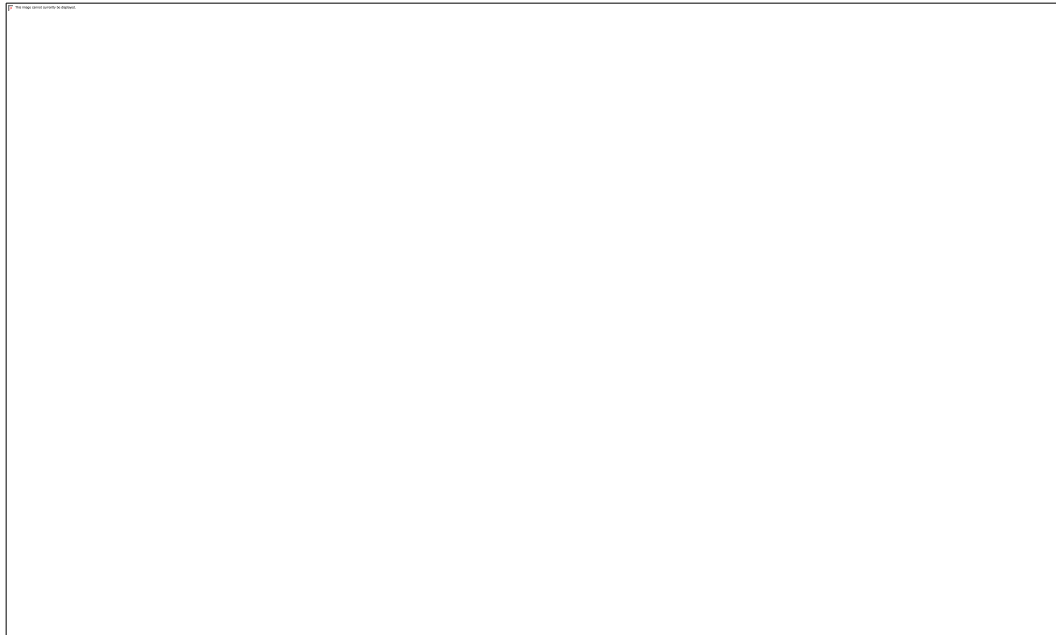
- Procedures and rules for
 - Low damping natural rubber
 - Lead-rubber
 - Friction Pendulum type
- Stable, predictable hysteresis



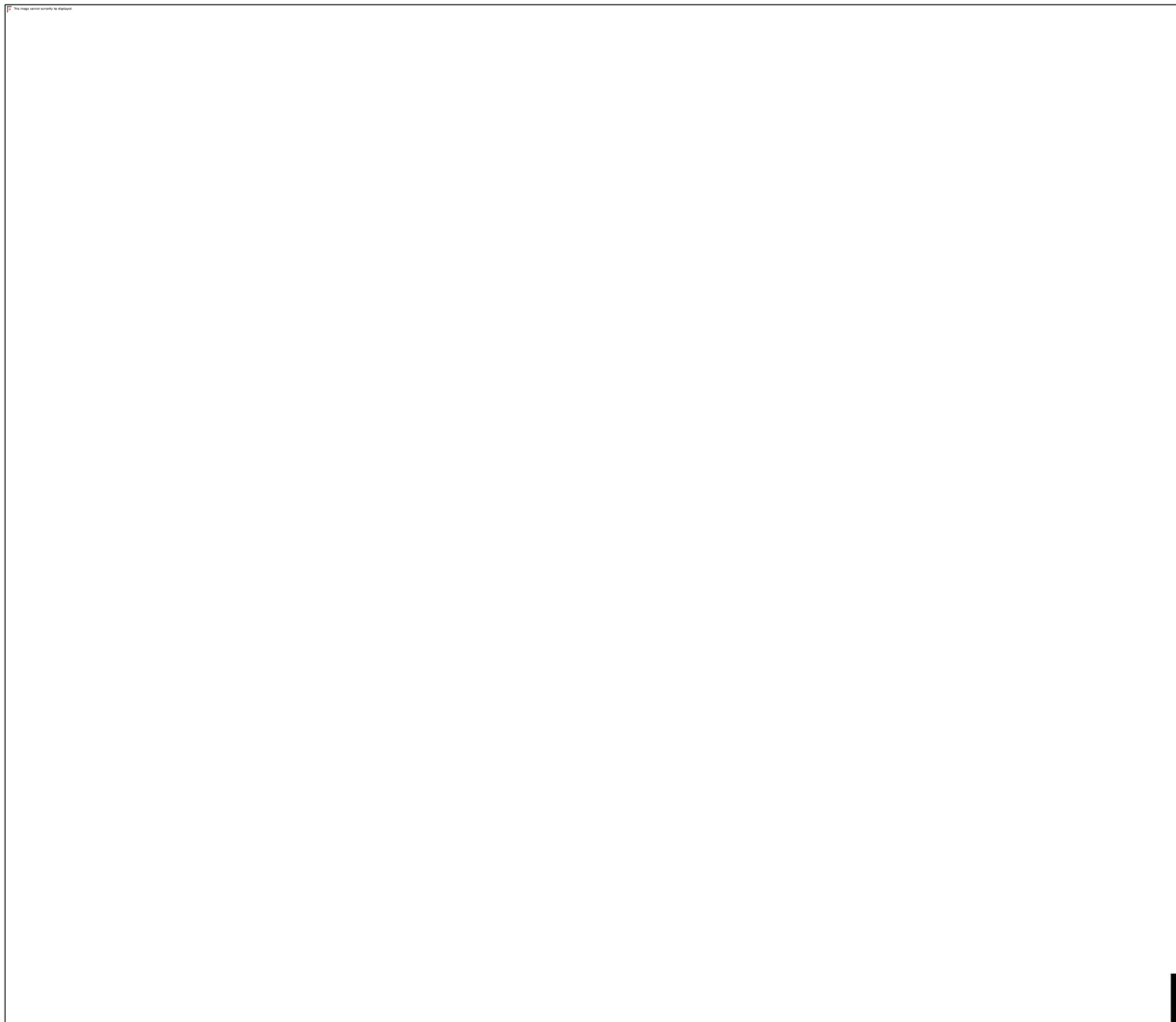
Isolators and isolation systems

- Developments funded by USNRC
 - Focus on behavior under extreme loadings
- Verified and validated models per ASME
 - OpenSees, ABAQUS and LS-DYNA
 - Friction Pendulum bearing
 - Low damping rubber bearing
opensees.berkeley.edu/wiki/index.php/ElastomericX
 - Lead rubber bearing
opensees.berkeley.edu/wiki/index.php/LeadRubberX
 - High damping rubber bearing
opensees.berkeley.edu/wiki/index.php/HDR

Risk calculations

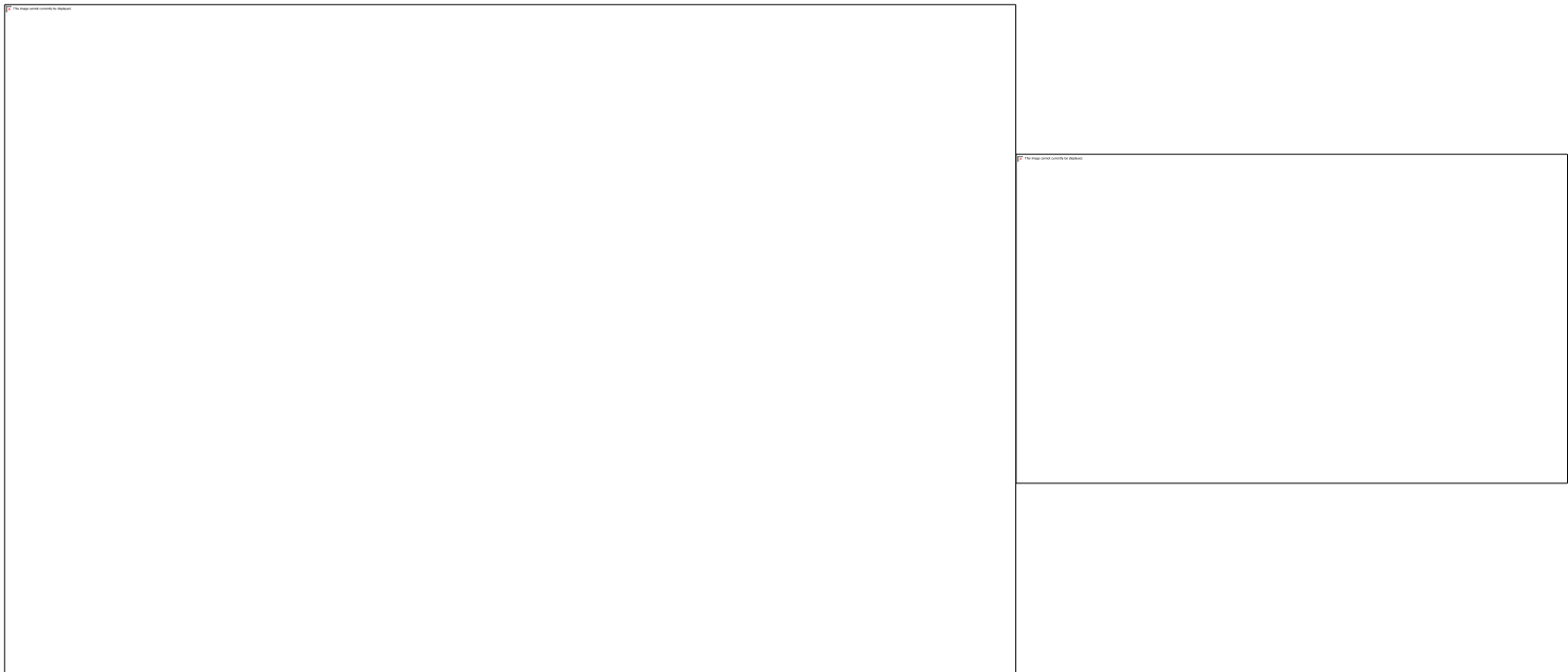


Sites of nuclear facilities in the US



Sites of nuclear facilities in the US

- Return periods for S_a at 1 s

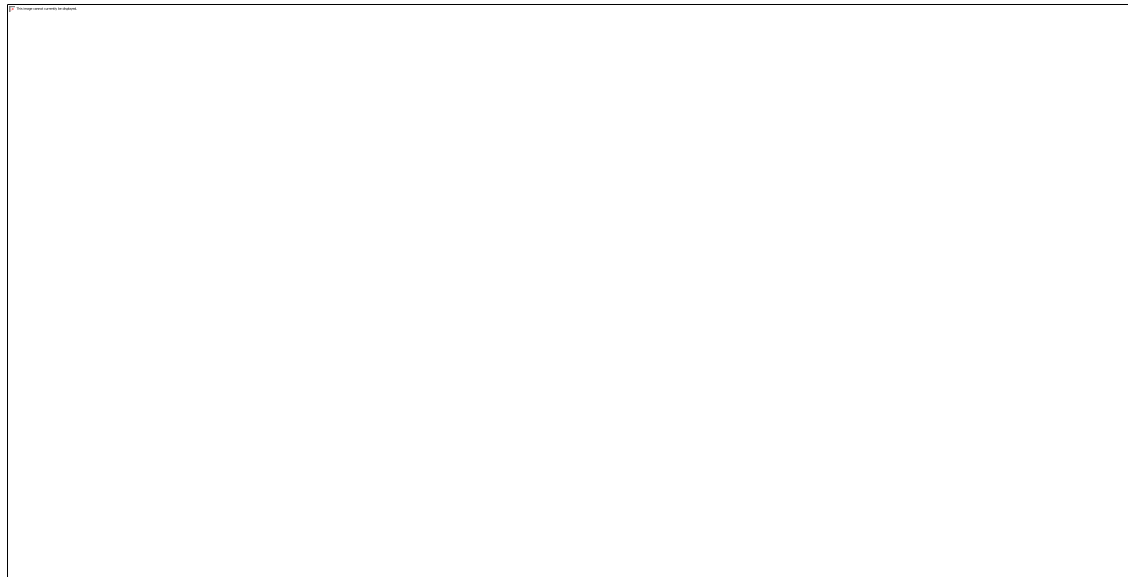


Seismic hazard curves



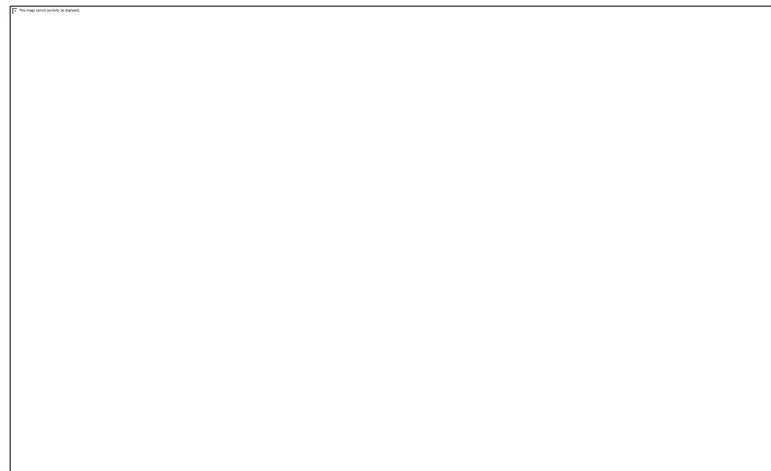
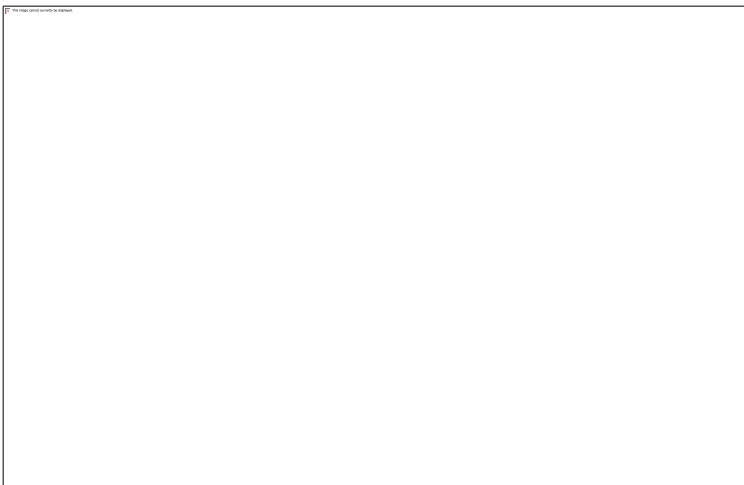
Seismic hazard curves

- Defined as multiples, m , of GMRS+
 - Computed in terms of average of multiples of spectral ordinates at 1 s and 2 s
 - $DF = 1$



Median fragility curves: NRC space

- Isolation system and individual isolators
 - Assumed fully correlated
 - Lognormal distribution parameters
 - Variability small for high quality isolators
 - Median 110% EDB GMRS displacement $\geq 90^{\text{th}}$ percentile EDB GMRS displacement



Risk calculations: NRC space

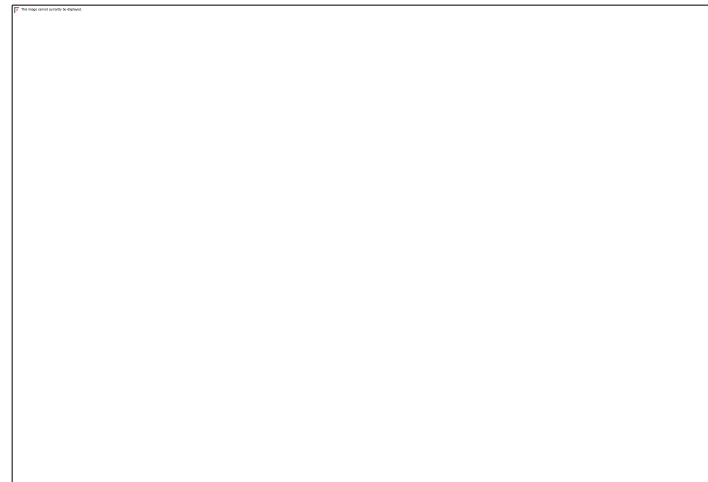
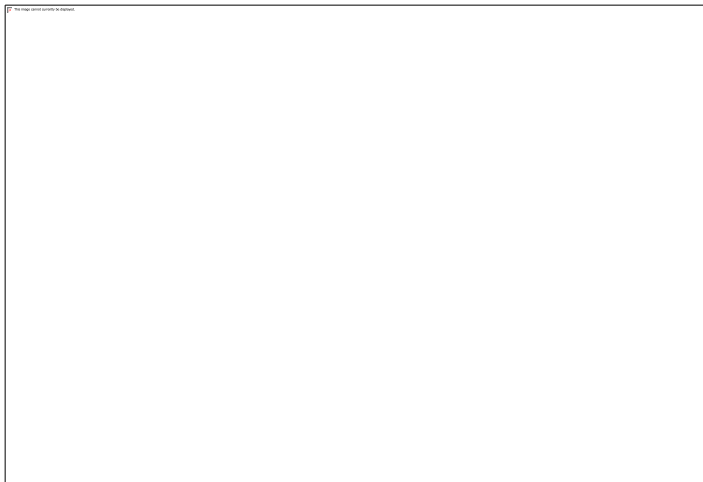


Risk calculations: NRC space



Median fragility curves: DoE space

- Isolation system
 - Assumed fully correlated
 - Lognormal distribution parameters
 - Variability small for high quality isolators
 - Median 165% (220%) DRS displacement = 90th percentile 150% (200%) DRS displacement



Risk calculations: DoE space



Risk calculations: DoE space



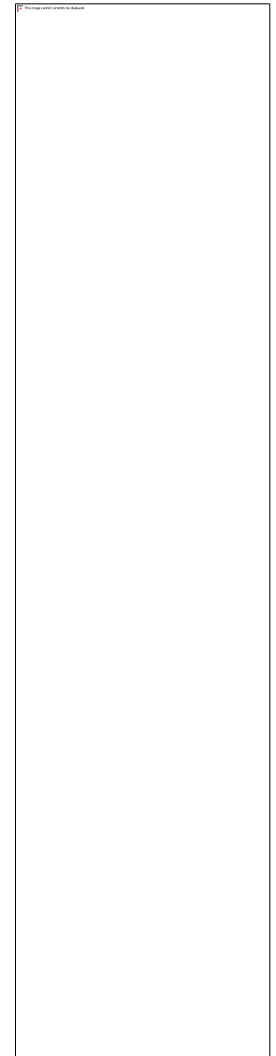
On-going nuclear-related studies

- PRA methodologies to address isolation
 - Huang et al. 2009, Lungmen NPP
- Nonlinear SSI analysis
 - Numerical and physical simulations
 - Hybrid simulations
- RC and SC shear walls
 - Design procedures and fragility functions
- Missile impact on RC and SC walls
- Isolation of components and subsystems
 - Integration with SSI



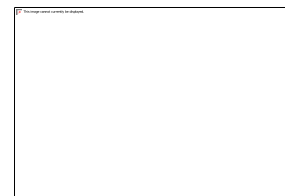
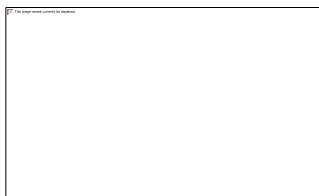
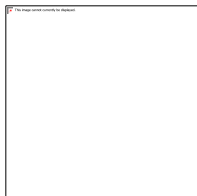
On-going nuclear-related studies

- Component isolation
 - 3D isolation possible
 - Component geometry and fragility
 - Different from LLWR
 - Isolator design for non-seismic fragility
 - Alternate isolator(s)
 - Family of component isolators
 - Extend Chapter 10(12) of ASCE 4(43)
 - Expand seismic isolation NUREG
 - Fully coupled time domain analysis
 - Seismic input filtered by structure



Acknowledgments

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- Robert Budnitz
- Jim Johnson
- Robert Kennedy



Isolators and isolation systems

- Qualification of *other* types of isolators
 - Dynamic testing of prototype isolators for BDBE demands
 - Development of V+V numerical models of the isolator capable of predicting response under extreme loadings
 - Isolator MUST be “analyzable” for extreme loadings
 - Basic chemistry, lab tests and field applications to show that mechanical properties do not change by more than 20% over design life
 - System level testing using 3D inputs
 - V+V of numerical tools to predict response of the isolation system